Plasma Heating by Gas-Dynamic Shocks in Thin Post-reconnection Flux Tubes

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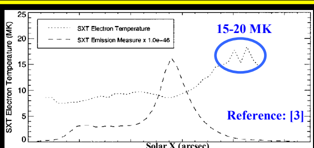
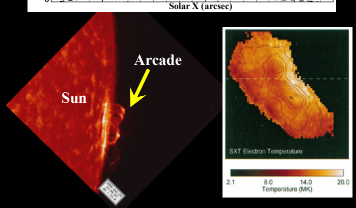
Summary

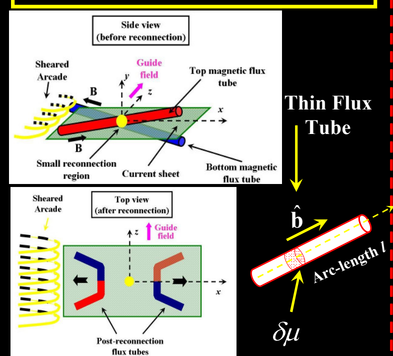
- We study the evolution of a post-reconnection thin flux tube.
- Motivation: Explain temperatures of 20 MK on top of arcades.
- We present the first model of gas-dynamic shocks (GDSs) along post-reconnection thin flux tubes. GDSs can heat the plasma up to the observed temperatures.
- In the solar corona, viscosity and thermal conductivity are large along the magnetic field. We developed a code, called DEFT, that simulates the retraction of a thin reconnected tube, and includes ANISOTROPIC transport coefficients, as well as their strong dependence on temperature (~T^5/2). These transport coefficients determine the detailed inner structure of the shock.
- For high thermal conductivity, the internal structure of the shock presents an isothermal sub-shock, as well as a heat front (this last one can be as large as the entire flux tube).
- Simulations are carried out using REAL CORONAL PARAMETERS: Prandtl number ≈ 0.01, Viscous Reynolds number ≈ 10^4, beta ≈ 0.01

Motivation





Patchy Reconnection



Modified Low β Thin Flux Tube Equations (unitless)

Mass Equation:

$$\delta\mu = \frac{\delta m}{\phi} = \frac{\rho}{B}\delta l = const$$

Momentum Equation:

$$\rho\left(\frac{D\mathbf{v}}{Dt}\right)_{\delta\mu} = 2\mathbf{k}\left(\frac{B_e^2}{8\pi}\right)\left(1-\frac{\beta}{2}\right) + \frac{\partial}{\partial l}\left[\hat{\mathbf{b}}\,\eta\left(\hat{\mathbf{b}}\cdot\frac{\partial\mathbf{v}}{\partial l}\right)\right] - \boxed{\hat{\mathbf{b}}\frac{\partial P}{\partial l}}$$

Curvature vector; Viscosity

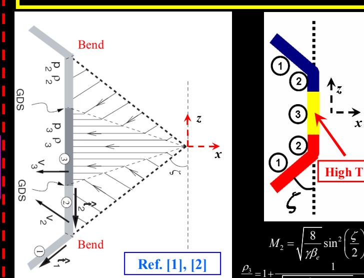
Entropy/Energy Equations:

$$\frac{D}{Dt}P_0 = (\gamma-1)\left(\frac{\rho_0}{\rho}\right)^{\gamma}\left\{\eta\left(\hat{\mathbf{b}}\cdot\frac{\partial\mathbf{v}}{\partial l}\right)^2 + \frac{\partial}{\partial l}\left(\kappa\frac{\partial}{\partial l}(T)\right)\right\}$$

Thermal Conductivity; Viscous Heat

$$P_0 = P\left(\frac{\rho_0}{\rho}\right)^{\gamma} = \mathrm{Exp}\left[\frac{s}{c_v}\right] \qquad \varepsilon = \frac{3}{2}\frac{P}{\rho}$$

Gas-Dynamic Shocks (GDSs)



$$M_2 = \sqrt{\frac{8}{\gamma\beta_e}}\sin^2\left(\frac{\zeta}{2}\right)$$

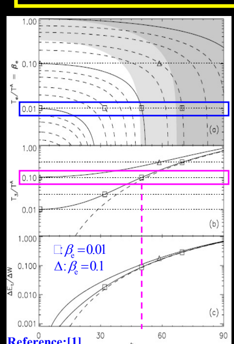
$$\frac{\rho_2}{\rho_e} = 1 + \frac{1}{\sqrt{\left(\frac{1}{M_2}\right)^2 + \frac{(\gamma+1)^2}{16}} - \frac{(3-\gamma)}{4}}$$

Jump conditions:

$$\rho_1, \beta_1 = \rho_2, \beta_2 = \rho_e, \beta_e \qquad \mathrm{v}_{1\|} = \mathrm{v}_{2\|} = \mathrm{v}_{Ae}$$

$$\frac{\beta_2}{\beta_e} = 1 + \gamma M_2^2\left[1 + \sqrt{\left(\frac{1}{M_2}\right)^2 + \frac{(\gamma+1)^2}{16}} - \frac{(3-\gamma)}{4}\right]$$

Plasma Heating



$$T^A := \frac{m_p \mathrm{v}_{Ae}^2}{4k_B} = 2\times10^8 K$$

$$\begin{pmatrix} 15\ \mathrm{G} \\ n_r = 3\times10^8\ \mathrm{cm}^{-3} \end{pmatrix}$$

$$\beta_e = \frac{T_e}{T^A}$$

$T_e = 2$ MK $\quad \beta_e = 0.01$

$$\boxed{20\ \mathrm{MK} \Leftarrow \zeta \approx 50^\circ}$$

ΔW := Available Magnetic Energy
ΔE_t := ConvertedThermal Energy

Corona Dimensionless Parameters

$$\mathrm{Beta}: \beta \sim 0.01$$

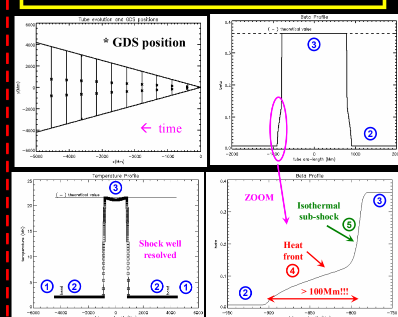
$$\mathrm{Reynolds}: R_\eta = \frac{L v_A \rho}{\eta} > 10^4$$

$$\mathrm{Prandtl}: P_r = \frac{\eta}{\kappa}\frac{2}{m_p}\eta \sim 0.01$$

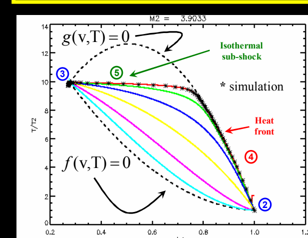
Transport Coefficients

$$\eta \sim T^{\frac{5}{2}} \qquad \kappa \sim T^{\frac{5}{2}}$$

DEFT Code Numerical Simulations: $\beta = 0.01$, $P_r = 0.01$, $R_\eta = 10^4$, ζ 50°



Fixed Point Diagram Ref.[4]



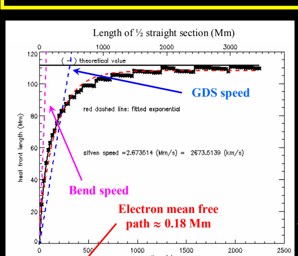
P_r =
0.01
0.03
0.1
0.3
1.0
3.0

$$\frac{\eta}{\mathbb{M}}\frac{d\mathrm{v}}{dl} = \mathrm{v} + \frac{\mathrm{T}}{\mathrm{v}} - \frac{\mathbb{P}}{\mathbb{M}} = g(\mathrm{v},\mathrm{T})$$

$$\frac{2\kappa}{\mathbb{M}}\frac{dT}{dl} = -\frac{\mathbb{Q}}{\mathbb{M}} + 2\mathrm{v}\frac{\mathbb{P}}{\mathbb{M}} + 3\mathrm{T} - \mathrm{v}^2 = f(\mathrm{v},\mathrm{T})$$

$$\mathbb{M} = \rho_2 \mathrm{v}_2 \qquad \mathbb{P} = \rho_2 \mathrm{v}_2^2 + P_2 \qquad \mathbb{Q} = \rho_2 \mathrm{v}_2^3 + 5\mathrm{v}_2 P_2$$

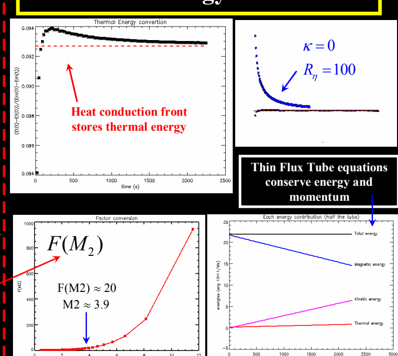
Heat Front



$$\sqrt{\frac{m_i}{2m_e}} \approx 31$$

$$L_{cond} = \frac{\boxed{K}}{c_{se}}\frac{c_{se}}{\sqrt{2}\,c_{si}}F(M_2) = \frac{\kappa}{n\,c_{se}}\boxed{\frac{c_{se}}{\sqrt{2}\,c_{si}}}F(M_2)$$

Thermal Energy conversion



Conclusions

- The shortening of the retracting tubes leads to compressive supersonic parallel flows that develop into Gas Dynamic Shocks that can heat the plasma up to observed temperatures (~20 MK on top of post-flare arcades), supporting the reconnection hypothesis.
- For high thermal conductivities, the internal structure of the shock presents an isothermal sub-shock, as well as a heat front (this last one can be as large as the entire flux tube!!).
- The heat front may drive chromospheric evaporation.
- Only less than 10% of the available energy is converted to thermal energy (including the heat front), but it is enough to heat plasma from 2MK to 20 MK.
- Our DEFT code is able to implement anisotropic transport coefficients, as well as realistic coronal parameters. This is almost impossible in 3D MHD simulations.
- The system does not reach the steady state asymptotic structures for realistic times (see "Heat Front" section).
- Our results can be easily extended to more realistic configurations like Y-type current sheets (Green-Syrovatsky configuration), and stratified atmospheres. This is our plan for future work.

References

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Acknowledgements

This work was supported by NASA grant LWS05-0032, and NSF.
We thank Dr. Mark Linton from the Naval Research Laboratory in Washington DC, for his collaboration in this project.